

**Dalitz plot analysis of  $D_s^+ \rightarrow \pi^+ \pi^- \pi^+$** 

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A Dalitz plot analysis of approximately 13 000  $D_s^+$  decays to  $\pi^+\pi^-\pi^+$  has been performed. The analysis uses a  $384\text{ fb}^{-1}$  data sample recorded by the *BABAR* detector at the PEP-II asymmetric-energy  $e^+e^-$  storage ring running at center of mass energies near 10.6 GeV. Amplitudes and phases of the intermediate resonances which contribute to this final state are measured. A high precision measurement of the ratio of branching fractions is performed:  $\mathcal{B}(D_s^+ \rightarrow \pi^+\pi^-\pi^+)/\mathcal{B}(D_s^+ \rightarrow K^+K^-\pi^+) = 0.199 \pm 0.004 \pm 0.009$ . Using a model-independent partial wave analysis, the amplitude and phase of the  $S$  wave have been measured.

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## I. INTRODUCTION

Dalitz plot analysis is an excellent way to study the dynamics of three-body charm decays. These decays are expected to proceed predominantly through intermediate quasi-two-body modes [1] and experimentally this is the observed pattern. Dalitz plot analyses can provide new information on the resonances that contribute to the observed three-body final states. In addition, since the intermediate quasi-two-body modes are dominated by light quark meson resonances, new information on light meson spectroscopy can be obtained.

Some puzzles still remain in light meson spectroscopy. There are new claims for the existence of broad states close to threshold such as  $\kappa(800)$  and  $f_0(600)$  [2]. The new evidence has reopened discussion of the composition of the ground state  $J^{PC} = 0^{++}$  nonet, and of the possibility that states such as the  $a_0(980)$  or  $f_0(980)$  may be 4-quark states, due to their proximity to the  $K\bar{K}$  threshold [3]. This hypothesis can be tested only through accurate measurements of the branching fractions and the couplings to different final states. It is therefore important to have precise information on the structure of the  $\pi\pi S$  wave. In addition, comparison between the production of these states in decays of differently flavored charmed mesons  $D^0(c\bar{u})$ ,  $D^+(c\bar{d})$  and  $D_s^+(c\bar{s})$  can yield new information on their possible quark composition. In this context,  $D_s^+$  mesons can give information on the structure of the scalar amplitude coupled to  $s\bar{s}$ . Another benefit of studying charm decays is that, in some cases, partial wave analyses are able to isolate the scalar contribution with almost no background.

This paper focuses on the study of the three-body  $D_s^+$  meson decays to  $\pi^+\pi^-\pi^+$  [4] and performs, for the first time, a model-independent partial wave analysis (MIPWA) [5]. Previous Dalitz plot analyses of this decay mode were based on much smaller data samples [6,7] and did not have sufficient statistics to perform the detailed analysis reported here.

This paper is organized as follows. Section II briefly describes the *BABAR* detector, while Sec. III gives details

on event reconstruction. Section IV is devoted to the evaluation of the selection efficiency. Section V deals with the Dalitz plot analysis of  $D_s^+ \rightarrow \pi^+\pi^-\pi^+$  and results are given in Sec. VI. The measurement of the  $D_s^+$  branching fraction is described in Sec. VII.

## II. THE *BABAR* DETECTOR AND DATA SET

This analysis is based on data collected with the *BABAR* detector at the PEP-II asymmetric-energy  $e^+e^-$  collider at Stanford Linear Accelerator Center (SLAC). The data sample used in this analysis corresponds to an integrated luminosity of  $347.5\text{ fb}^{-1}$  recorded at the  $\Upsilon(4S)$  resonance (on-peak) and  $36.5\text{ fb}^{-1}$  collected 40 MeV below the resonance (off-peak). The *BABAR* detector is described in detail elsewhere [8]. The following is a brief summary of the components important to this analysis. Charged particles are detected and their momenta measured by a combination of a cylindrical drift chamber (DCH) and a silicon vertex tracker (SVT), both operating within a 1.5 T solenoidal magnetic field. A ring-imaging Cherenkov detector (DIRC) is used for charged-particle identification. Photon energies are measured with a CsI electromagnetic calorimeter (EMC). Information from the DIRC and energy-loss measurements in the DCH and SVT are used to identify charged kaon and pion candidates. Monte Carlo (MC) events used in this analysis,  $e^+e^- \rightarrow c\bar{c}$ , are generated using the JETSET program [9], and the generated particles are propagated through a model of the *BABAR* detector with the GEANT4 simulation package [10]. Radiative corrections for signal and background processes are simulated using PHOTOS [11].

## III. EVENT SELECTION AND $D_s^+$ RECONSTRUCTION

Events corresponding to the three-body decay

$$D_s^+ \rightarrow \pi^+\pi^-\pi^+ \quad (1)$$

are reconstructed from the sample of events having at least three reconstructed charged tracks with a net charge of  $\pm 1$



and having a minimum transverse momentum of 0.1 GeV/c. Tracks from  $D_s^+$  decays are identified as pions or kaons by the Cherenkov angle  $\theta_c$  measured with the DIRC. The typical separation between pions and kaons varies from  $8\sigma$  at 2 GeV/c to  $2.5\sigma$  at 4 GeV/c, where  $\sigma$  is the average resolution on  $\theta_c$ . Lower momentum kaons are identified with a combination of  $\theta_c$  (for momenta down to 0.7 GeV/c) and measurements of ionization energy loss  $dE/dx$  in the DCH and SVT. The particle identification efficiency is  $\approx 95\%$ , while the misidentification rate for kaons is  $\approx 5\%$ . Photons are identified as EMC clusters that do not have a spatial match with a charged track and that have a minimum energy of 100 MeV. To reject background, the lateral energy is required to be less than 0.8. The three tracks are fitted to a common vertex, and the  $\chi^2$  fit probability (labeled  $P_1$ ) must be greater than 0.1%. A separate kinematic fit which makes use of the  $D_s^+$  mass constraint, to be used in the Dalitz plot analysis, is also performed. To help discriminate signal from background, an additional fit which uses the constraint that the three tracks originate from the  $e^+e^-$  luminous region (beam spot) is performed. We label the  $\chi^2$  probability of this fit as  $P_2$ , and it is expected to be large for background and small for  $D_s^+$  signal events, since in general the latter will have a measurable flight distance.

The combinatorial background is reduced by requiring the  $D_s^+$  to originate from the decay

$$D_s^*(2112)^+ \rightarrow D_s^+ \gamma \quad (2)$$

using the mass difference  $\Delta m = m(\pi^+ \pi^- \pi^+ \gamma) - m(\pi^+ \pi^- \pi^+)$ . We cannot reliably extract the  $D_s^*(2112)^+$  characteristics using the  $3\pi$  decay mode due to the large background below the signal peak. Therefore we use the decay

$$D_s^+ \rightarrow K^+ K^- \pi^+, \quad (3)$$

which has a much larger signal to background ratio. Fitting the mass difference  $\Delta m = m(K^+ K^- \pi^+ \gamma) - m(K^+ K^- \pi^+)$  for this decay mode with a polynomial describing the background and a single Gaussian for the signal, we obtain a width  $\sigma = 5.51 \pm 0.04$  MeV/c<sup>2</sup>. Since the experimental resolution in  $\Delta m$  is similar for the two  $D_s^+$  decay modes, we require the value of  $\Delta m$  for the  $D_s^+ \rightarrow \pi^+ \pi^- \pi^+$  mode to be within  $\pm 2\sigma$  of the Review of Particle Physics [12] value of the  $[D_s^*(2112)^+ - D_s^+]$  mass difference. At this stage the three-pion invariant mass signal region, defined between  $(-2\sigma, 2\sigma)$ , where  $\sigma$  is estimated by a Gaussian fit to the  $D_s^+$  line shapes, has a purity [signal/(signal + background)] of 4.3%.

Each  $D_s^+$  candidate is characterized by three variables: the center of mass momentum  $p^*$ , the difference in probability  $P_1 - P_2$ , and the signed decay distance  $d_{xy}$  between the  $D_s^+$  decay vertex and the beam spot projected in the plane normal to the beam collision axis. The distributions for these variables for background are inferred from the  $D_s^+ \rightarrow \pi^+ \pi^- \pi^+$  invariant mass sidebands defined be-

tween  $(-9\sigma, -5\sigma)$  and  $(5\sigma, 9\sigma)$ . Since these variables are (to a good approximation) independent of the decay mode, the distributions for the three-pion invariant mass signal are inferred from the  $D_s^+ \rightarrow K^+ K^- \pi^+$  decay. These normalized distributions are then combined in a likelihood ratio test. The cut on the likelihood ratio has been chosen in order to obtain the largest statistics with background small enough to perform a Dalitz plot analysis.

Many possible background sources are examined. A small background contribution due to the decay  $D^{*+} \rightarrow \pi^+ D^0$ , where  $D^0 \rightarrow \pi^+ \pi^-$ , is addressed by removing

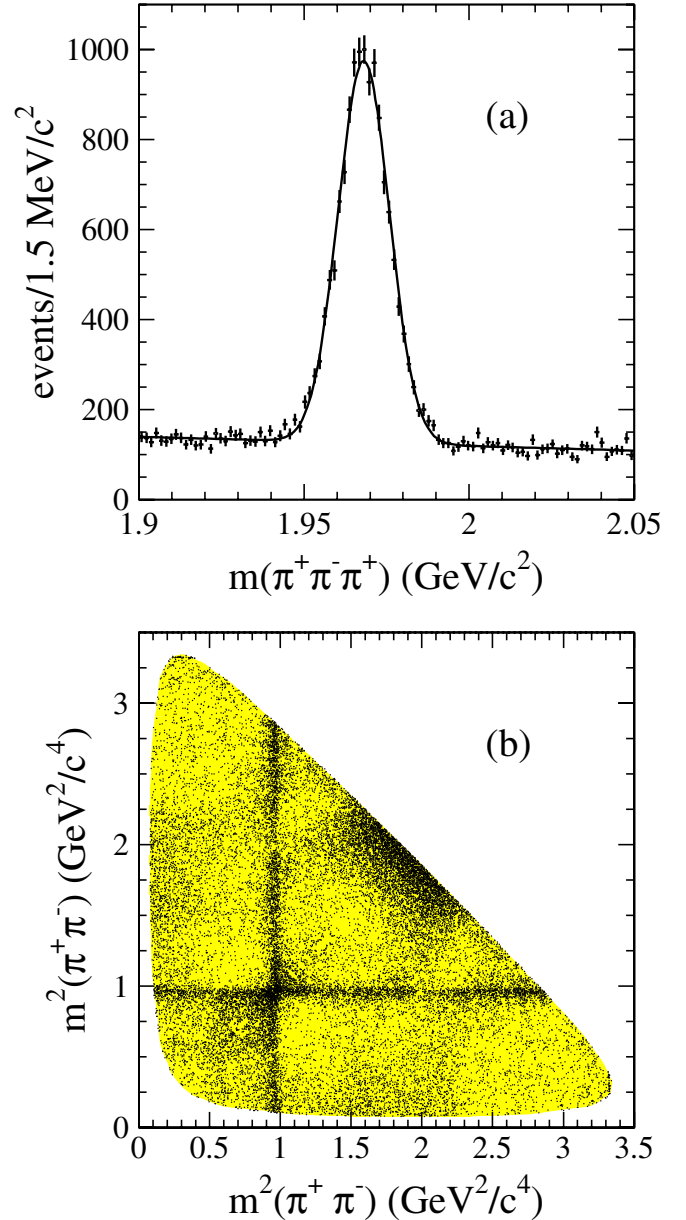


FIG. 1 (color online). (a)  $\pi^+ \pi^- \pi^+$  invariant mass distribution for the  $D_s^+$  analysis sample. The line is the result of the fit described in the text. (b) Symmetrized  $D_s^+ \rightarrow \pi^+ \pi^- \pi^+$  Dalitz plot (two entries per event).

events with  $|m(\pi^+\pi^-) - m_{D^0}| < 20.7 \text{ MeV}/c^2$  and  $m(\pi^+\pi^-\pi^+) - m(\pi^+\pi^-) < 0.1475 \text{ GeV}/c^2$ . Particle misidentification, in which a kaon ( $K_{\text{mis}}$ ) is wrongly identified as a pion, is tested by assigning the kaon mass to each pion in turn. In this way we observe a clean signal in the mass difference  $m(\pi^+K_{\text{mis}}^-\pi^+) - m(\pi^+K_{\text{mis}}^-)$  due to the decay  $D^{*+} \rightarrow \pi^+D^0$ , where  $D^0 \rightarrow K_{\text{mis}}^-\pi^+$ . Removing events with  $|m(K_{\text{mis}}^-\pi^+) - m_{D^0}| < 21.7 \text{ MeV}/c^2$  and  $m(\pi^+K_{\text{mis}}^-\pi^+) - m(K_{\text{mis}}^-\pi^+) < 0.1475 \text{ GeV}/c^2$  diminishes this background. Finally, events having more than one candidate are removed from the sample (1.2% of the events).

The resulting  $\pi^+\pi^-\pi^+$  mass distribution is shown in Fig. 1(a). This distribution has been fitted with a single Gaussian for the signal and a linear background function. The fit gives a  $D_s^+$  mass of  $(1968.1 \pm 0.1) \text{ MeV}/c^2$  and width  $\sigma = 7.77 \pm 0.09 \text{ MeV}/c^2$  (statistical error only). The signal region contains 13 179 events with a purity of 80%. The resulting Dalitz plot, symmetrized along the two axes, is shown in Fig. 1(b). For this distribution, and in the following Dalitz plot analysis, we use the track momenta obtained from the  $D_s^+$  mass-constrained fit. We observe a clear  $f_0(980)$  signal, evidenced by the two narrow crossing bands. We also observe a broad accumulation of events in the  $1.9 \text{ GeV}^2/c^4$  region.

#### IV. EFFICIENCY

The efficiency for this  $D_s^+$  decay mode is determined from a sample of Monte Carlo events in which the  $D_s^+$  decay is generated according to phase space (i.e. such that the Dalitz plot is uniformly populated). These events are passed through a full detector simulation and subjected to the same reconstruction and event selection procedure applied to the data. The distribution of the selected events in the Dalitz plot is then used to determine the total reconstruction and selection efficiency. The MC sample  $e^+e^- \rightarrow D_s^{*+}X$ , where  $D_s^{*+} \rightarrow \gamma D_s^+$ , used to compute this efficiency consists of  $27.4 \times 10^6$  generated events for  $D_s^+ \rightarrow \pi^+\pi^-\pi^+$  and  $4.2 \times 10^6$  for  $D_s^+ \rightarrow K^+K^-\pi^+$ . The Dalitz plot is divided into small cells and the efficiency distribution is fitted with a second-order polynomial in two dimensions. The efficiency is found to be almost uniform as a function of the  $\pi^+\pi^-$  invariant mass with an average value of  $\approx 1.6\%$ . This low efficiency is mainly due to the likelihood ratio selection: it is 18.0% without this cut.

The experimental resolution as a function of the  $\pi^+\pi^-$  mass has been computed as the difference between MC generated and reconstructed mass. It increases from 1.0 to 2.5  $\text{MeV}/c^2$  from the  $\pi^+\pi^-$  threshold to 1.0  $\text{GeV}/c^2$ .

#### V. DALITZ PLOT ANALYSIS

An unbinned maximum likelihood fit is performed on the distribution of events in the Dalitz plot to determine the relative amplitudes and phases of intermediate resonant and nonresonant states. The likelihood function is

$$\mathcal{L} = \prod_{\text{events}} \left[ x(m) \cdot \eta(m_1^2, m_2^2) \frac{\sum_{i,j} c_i c_j^* A_i A_j^*}{\sum_{i,j} c_i c_j^* I_{A_i A_j^*}} + (1 - x(m)) \frac{\sum_i |k_i|^2 B_i^2}{\sum_i |k_i|^2 I_{B_i^2}} \right], \quad (4)$$

where

- (i)  $m_1^2$  and  $m_2^2$  are the squared  $\pi^+\pi^-$  effective masses.
- (ii)  $x(m)$  is the mass-dependent fraction of signal, defined as  $x(m) = \frac{G(m)}{G(m)+P(m)}$ . Here  $G(m)$  and  $P(m)$  represent the Gaussian and the linear function used to fit the  $\pi^+\pi^-\pi^+$  mass spectrum, respectively.
- (iii)  $\eta(m_1^2, m_2^2)$  is the efficiency, parametrized with a two-dimensional second-order polynomial.
- (iv)  $A_i$  and  $B_i$  describe signal and background amplitude contributions, respectively.
- (v)  $k_i$  are real factors describing the structure of background. They are computed by fitting the sideband regions.
- (vi)  $I_{A_i A_j^*} = \int A_i A_j^* \eta(m_1^2, m_2^2) dm_1^2 dm_2^2$  and  $I_{B_i^2}$  are the normalization integrals for signal and background, respectively. The products of efficiency and amplitudes are normalized using a numerical integration over the Dalitz plot.
- (vii)  $c_i$  are complex coefficients allowed to vary during the fit procedure.

The efficiency-corrected fraction due to the resonant or nonresonant contribution  $i$  is defined as follows:

$$f_i = \frac{|c_i|^2 \int |A_i|^2 dm_1^2 dm_2^2}{\sum_{j,k} c_j c_k^* \int A_j A_k^* dm_1^2 dm_2^2}. \quad (5)$$

The  $f_i$  values do not necessarily add to 1 because of interference effects. The uncertainty on each  $f_i$  is evaluated by propagating the full covariance matrix obtained from the fit.

The phase of each amplitude (i.e. the phase of the corresponding  $c_i$ ) is measured with respect to the  $f_2(1270)\pi^+$  amplitude. Each  $\mathcal{P}$  wave and  $\mathcal{D}$  wave amplitude  $A_i$  is represented by the product of a complex Breit-Wigner function [BW( $m$ )] and a real angular term:

$$A = \text{BW}(m) \times T(\Omega), \quad (6)$$

where  $m$  is the  $\pi^+\pi^-$  mass. The Breit-Wigner function includes the Blatt-Weisskopf form factors [13]. The angular terms  $T(\Omega)$  are described in Ref. [12].

For the  $\pi^+\pi^-$   $S$  wave amplitude, we use a different approach because

- (i) Scalar resonances have large uncertainties. In addition, the existence of some states needs confirmation.
- (ii) Modeling the  $S$  wave as a superposition of Breit-Wigner functions is unphysical since it leads to a violation of unitarity when broad resonances overlap.

To overcome these problems, we use a model-independent partial wave analysis introduced by the Fermilab E791 Collaboration [5]: instead of including the  $S$  wave amplitude as a superposition of relativistic Breit-Wigner functions, we divide the  $\pi^+ \pi^-$  mass spectrum into 29 slices and we parametrize the  $S$  wave by an interpolation between the 30 end points in the complex plane:

$$A_{S \text{ wave}}(m_{\pi\pi}) = \text{Interp}(c_k(m_{\pi\pi})e^{i\phi_k(m_{\pi\pi})})_{k=1,\dots,30}. \quad (7)$$

The amplitude and phase of each end point are free pa-

rameters. The width of each slice is tuned to get approximately the same number of  $\pi^+ \pi^-$  combinations ( $\approx 13\,179 \times 2/29$ ). Interpolation is implemented by a relaxed cubic spline [14]. The phase is not constrained in a specific range in order to allow the spline to be a continuous function.

The background shape is obtained by fitting the  $D_s^+$  sidebands. In this fit, resonances are assumed to be incoherent, i.e. are represented by Breit-Wigner intensity terms only. A good representation of the background includes

TABLE I. Results from the  $D_s^+ \rightarrow \pi^+ \pi^- \pi^+$  Dalitz plot analysis. The table reports the fit fractions, amplitudes and phases. Errors are statistical and systematic, respectively.

Decay mode	Decay fraction (%)	Amplitude	Phase (rad)
$f_2(1270)\pi^+$	$10.1 \pm 1.5 \pm 1.1$	1.0 (fixed)	0.0 (fixed)
$\rho(770)\pi^+$	$1.8 \pm 0.5 \pm 1.0$	$0.19 \pm 0.02 \pm 0.12$	$1.1 \pm 0.1 \pm 0.2$
$\rho(1450)\pi^+$	$2.3 \pm 0.8 \pm 1.7$	$1.2 \pm 0.3 \pm 1.0$	$4.1 \pm 0.2 \pm 0.5$
$S$ wave	$83.0 \pm 0.9 \pm 1.9$	Table II	Table II
Total	$97.2 \pm 3.7 \pm 3.8$		
$\chi^2/\text{NDF}$	$\frac{437}{422-64} = 1.2$		

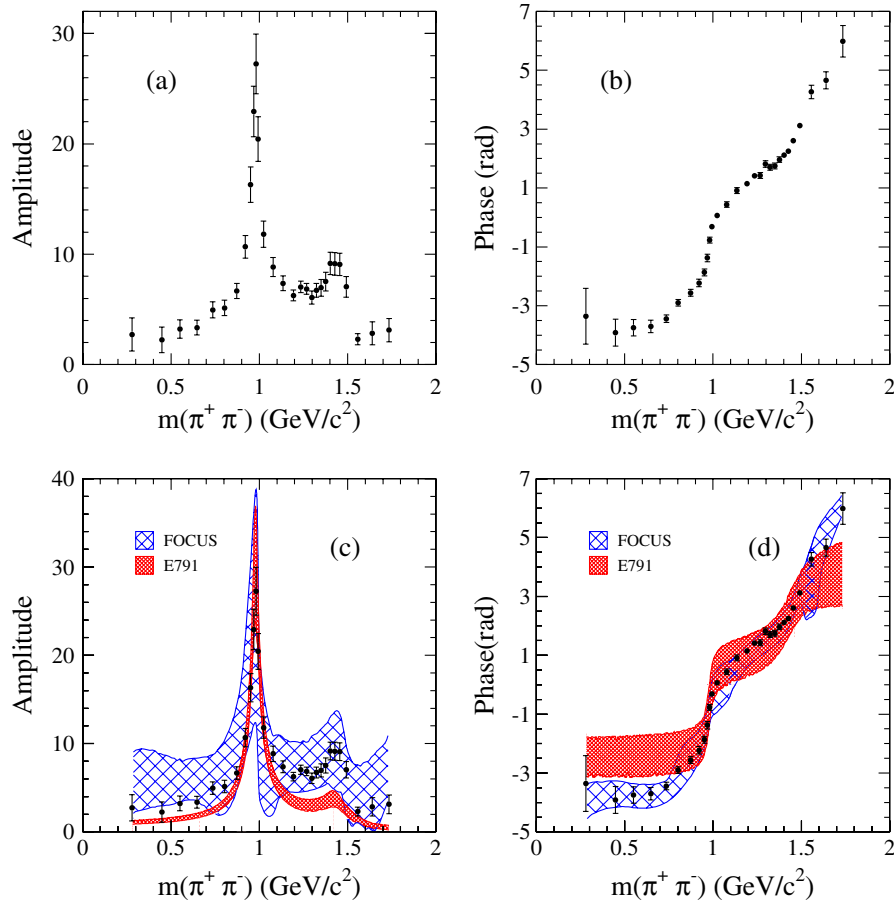


FIG. 2 (color online). (a)  $S$  wave amplitude extracted from the best fit, (b) corresponding  $S$  wave phase, (c)  $S$  wave amplitude compared to the FOCUS and E791 amplitudes, and (d)  $S$  wave phase compared to the FOCUS and E791 phases. Errors are statistical only.

contributions from  $K_S^0$ ,  $\rho^0(770)$  and three *ad hoc* scalar resonances with free parameters.

Resonances are included in sequence, keeping only those having a fractional significance greater than 2 standard deviations.

## VI. RESULTS

The fit results (fractions and phases) are summarized in Table I. The resulting  $\pi^+\pi^-$   $S$  wave amplitude and phase is shown in Figs. 2(a) and 2(b) and is given numerically in Table II. Figures 2(c) and 2(d) show a comparison with the resulting  $S$  wave from the E791 experiment, which performed a Dalitz plot analysis using an isobar model [6], and the FOCUS experiment, which made use of the  $K$ -matrix formalism [7]. In the two figures, the two bands have been obtained by propagating the measurement errors and assuming no correlations. This assumption may influence the calculation of the uncertainties on the phases and amplitudes which are different in the two experiments.

The Dalitz plot projections together with the fit results are shown in Fig. 3. Here we label with  $m^2(\pi^+\pi^-)_{\text{low}}$  and

TABLE II. Amplitude and phase of the  $\pi^-\pi^+$   $S$  wave amplitude determined with the MIPWA fit described in the text. The first error is statistical while the second is systematic.

Interval	Mass (GeV/ $c^2$ )	Amplitude	Phase (radians)
1	0.28	$2.7 \pm 1.5 \pm 2.4$	$-3.4 \pm 1.0 \pm 1.3$
2	0.448	$2.2 \pm 1.2 \pm 1.3$	$-3.9 \pm 0.5 \pm 0.4$
3	0.55	$3.2 \pm 0.8 \pm 1.1$	$-3.7 \pm 0.3 \pm 0.3$
4	0.647	$3.3 \pm 0.7 \pm 0.9$	$-3.7 \pm 0.2 \pm 0.3$
5	0.736	$5.0 \pm 0.7 \pm 1.1$	$-3.4 \pm 0.1 \pm 0.2$
6	0.803	$5.1 \pm 0.7 \pm 0.8$	$-2.9 \pm 0.1 \pm 0.2$
7	0.873	$6.7 \pm 0.7 \pm 0.7$	$-2.6 \pm 0.1 \pm 0.3$
8	0.921	$10.7 \pm 1.0 \pm 0.9$	$-2.2 \pm 0.1 \pm 0.2$
9	0.951	$16.3 \pm 1.6 \pm 1.2$	$-1.9 \pm 0.1 \pm 0.2$
10	0.968	$22.9 \pm 2.3 \pm 1.5$	$-1.4 \pm 0.1 \pm 0.1$
11	0.981	$27.2 \pm 2.7 \pm 1.6$	$-0.8 \pm 0.1 \pm 0.2$
12	0.993	$20.4 \pm 2.0 \pm 0.9$	$-0.3 \pm 0.1 \pm 0.2$
13	1.024	$11.8 \pm 1.2 \pm 0.5$	$0.1 \pm 0.1 \pm 0.2$
14	1.078	$8.8 \pm 0.9 \pm 0.3$	$0.4 \pm 0.1 \pm 0.1$
15	1.135	$7.4 \pm 0.7 \pm 0.3$	$0.9 \pm 0.1 \pm 0.1$
16	1.193	$6.3 \pm 0.5 \pm 0.2$	$1.1 \pm 0.1 \pm 0.1$
17	1.235	$7.0 \pm 0.5 \pm 0.3$	$1.4 \pm 0.1 \pm 0.1$
18	1.267	$6.9 \pm 0.5 \pm 0.3$	$1.4 \pm 0.1 \pm 0.1$
19	1.297	$6.1 \pm 0.6 \pm 0.6$	$1.8 \pm 0.1 \pm 0.1$
20	1.323	$6.7 \pm 0.6 \pm 0.5$	$1.7 \pm 0.1 \pm 0.1$
21	1.35	$7.0 \pm 0.8 \pm 0.6$	$1.8 \pm 0.1 \pm 0.2$
22	1.376	$7.5 \pm 0.8 \pm 0.7$	$2.0 \pm 0.1 \pm 0.1$
23	1.402	$9.2 \pm 1.0 \pm 0.9$	$2.1 \pm 0.1 \pm 0.1$
24	1.427	$9.1 \pm 1.0 \pm 0.9$	$2.3 \pm 0.1 \pm 0.2$
25	1.455	$9.1 \pm 1.0 \pm 1.6$	$2.6 \pm 0.1 \pm 0.1$
26	1.492	$7.0 \pm 0.9 \pm 1.1$	$3.1 \pm 0.1 \pm 0.2$
27	1.557	$2.3 \pm 0.5 \pm 0.7$	$4.3 \pm 0.2 \pm 0.4$
28	1.64	$2.8 \pm 1.1 \pm 1.3$	$4.7 \pm 0.3 \pm 0.7$
29	1.735	$3.1 \pm 1.1 \pm 2.3$	$6.0 \pm 0.5 \pm 1.4$

$m^2(\pi^+\pi^-)_{\text{high}}$  the lower and higher values, respectively, of the two  $\pi^+\pi^-$  mass combinations.

The fit projections are obtained by generating a large number of phase space MC events [15], weighting by the fit likelihood function, and normalizing the weighted sum to the observed number of events. There is good agreement between data and fit projections. Further tests of the fit quality are performed using unnormalized  $Y_L^0$  moment projections onto the  $\pi^+\pi^-$  axis as functions of the helicity angle  $\theta$ , which is defined as the angle between the  $\pi^-$  and the  $D_s^+$  in the  $\pi^+\pi^-$  rest frame (or  $\pi^+$  for  $D_s^-$ ) (two combinations per event). The  $\pi^+\pi^-$  mass distribution is then weighted by the spherical harmonic  $Y_L^0(\cos\theta)$  ( $L = 1 - 6$ ). The resulting distributions of the  $\langle Y_L^0 \rangle$  are shown in Fig. 4. A straightforward interpretation of these distributions is difficult, due to reflections originating from the symmetrization. However, the squares of the spin amplitudes appear in even moments, while interference terms appear in odd moments.

The fit produces a good representation of the data for all projections. The fit  $\chi^2$  is computed by dividing the Dalitz plot into  $30 \times 30$  cells with 422 cells having entries. We obtain  $\chi^2/NDF = 437/(422 - 64) = 1.2$ . The  $\chi^2$  is also calculated using an adaptive binning with an average number of events per cell  $\approx 35$  [ $\chi^2/NDF = 365/(391 - 64) = 1.1$ ], obtaining a  $\chi^2$  probability of 7.2%.

Attempts to include other resonant contributions, such as  $\omega(782)$  or  $f_2'(1525)$ , do not improve the fit quality. MC simulations have been performed in order to validate the method and test for possible multiple solutions.

The results from the Dalitz plot analysis can be summarized as follows:

- (i) The decay is dominated by the  $D_s^+ \rightarrow (\pi^+\pi^-)_{S \text{ wave}} \pi^+$  contribution.
- (ii) The  $S$  wave shows, in both amplitude and phase, the expected behavior for the  $f_0(980)$  resonance.
- (iii) The  $S$  wave shows further activity, in both amplitude and phase, in the regions of the  $f_0(1370)$  and  $f_0(1500)$  resonances.
- (iv) The  $S$  wave is small in the  $f_0(600)$  region, indicating that this resonance has a small coupling to  $s\bar{s}$ .
- (v) There is an important contribution from  $D_s^+ \rightarrow f_2(1270)\pi^+$  whose size is in agreement with that reported by FOCUS, but a factor of 2 smaller than that reported by E791. This is the largest contribution in charm decays from a spin-2 resonance.
- (vi) We observe a similar trend for the  $S$  wave amplitude and phase among the three experiments. Our results agree better (within uncertainties) with the results from FOCUS than those from E791.

Our results may be compared with different measurements of the  $\pi\pi$  amplitude and phase from many other sources. For a recent review, see [16].



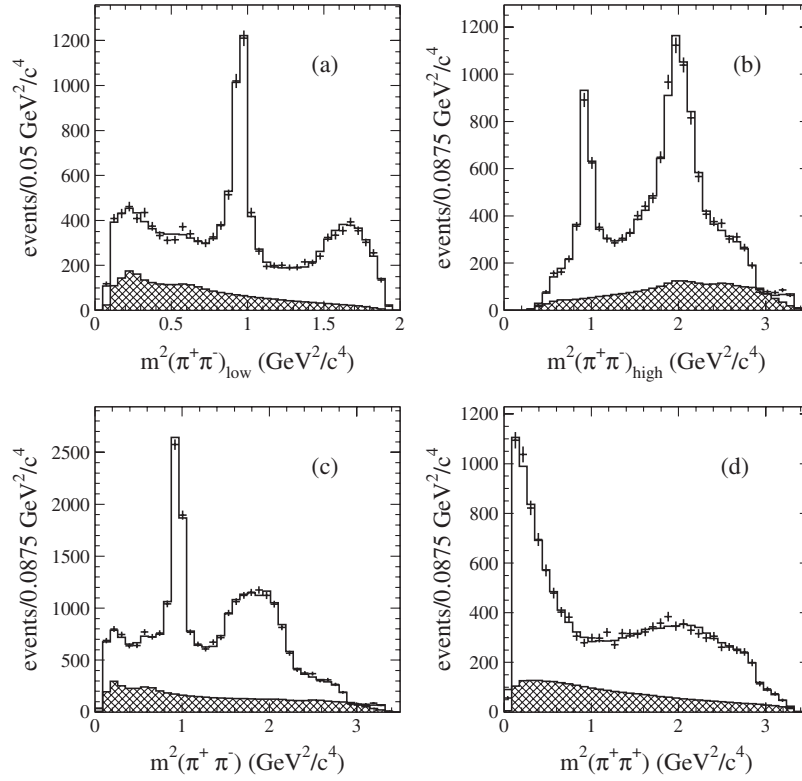


FIG. 3. Dalitz plot projections (points with error bars) and fit results (solid histogram). (a)  $m^2(\pi^+\pi^-)_{\text{low}}$ , (b)  $m^2(\pi^+\pi^-)_{\text{high}}$ , (c) total  $m^2(\pi^+\pi^-)$ , and (d)  $m^2(\pi^+\pi^+)$ . The hatched histograms show the background distribution.

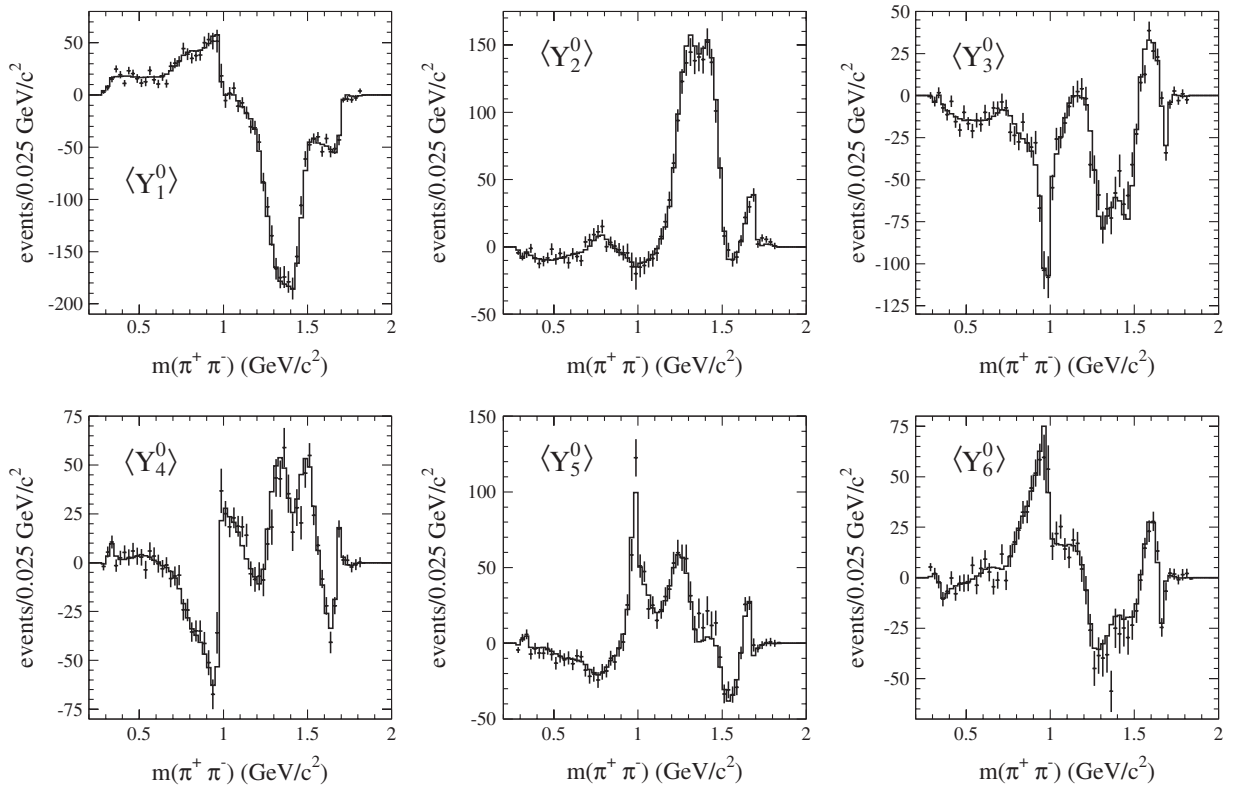


FIG. 4. Unnormalized spherical harmonic moments  $\langle Y_L^0 \rangle$  as a function of  $\pi^+\pi^-$  effective mass. The data are presented with error bars, and the histograms represent the fit projections.

Systematic uncertainties on the fitted fractions are evaluated in different ways:

- (i) The background parametrization is performed using the information from the lower/higher sideband only or both sidebands.
- (ii) The Blatt-Weisskopf barrier factors have a single parameter  $r$  which we take to be  $1.5 \text{ (GeV}/c)^{-1}$  and which has been varied between 0 and 3  $(\text{GeV}/c)^{-1}$ .
- (iii) Results from fits which give equivalent Dalitz plot descriptions and similar sums of fractions (but worse likelihood) are considered.
- (iv) The likelihood cut is relaxed but the mass cut on the  $\pi^+\pi^-\pi^+$  is narrowed in order to obtain a similar purity.
- (v) The purity of the signal, the resonance parameters and the efficiency coefficients are varied within their statistical errors.
- (vi) The  $\rho(770)$  and  $\rho(1450)$  parametrization is modified according to the Gounaris-Sakurai model [17].
- (vii) The number of steps used to describe the  $\mathcal{S}$  wave has been varied by  $\pm 2$ .

## VII. BRANCHING FRACTION

Since the two  $D_s^+$  decay channels (1) and (3) have similar topologies, the ratio of branching fractions is expected to have a reduced systematic uncertainty. We therefore select events from the two  $D_s^+$  decay modes using similar selection criteria for the  $D_s^{*+}$  selection and for the likelihood test. For this measurement, a looser likelihood cut is used.

The ratio of branching fractions is evaluated as

$$\text{BR} = \frac{\sum_{x,y} \frac{N_i(x,y)}{\epsilon_i(x,y)}}{\sum_{x,y} \frac{N_0(x,y)}{\epsilon_0(x,y)}}, \quad (8)$$

where  $N_i(x, y)$  represents the number of events measured for channel  $i$ , and  $\epsilon_i(x, y)$  is the corresponding efficiency in a given Dalitz plot cell  $(x, y)$ . For this calculation each Dalitz plot was divided into  $50 \times 50$  cells.

To obtain the yields and measure the relative branching fractions, the  $\pi^+\pi^-\pi^+$  and  $K^+K^-\pi^+$  mass distributions are fit assuming a double Gaussian signal and linear background where all the parameters are floated. Systematic uncertainties, summarized in Table III, take into account uncertainties from MC statistics and from the selection criteria used.

The resulting ratio is

$$\frac{\mathcal{B}(D_s^+ \rightarrow \pi^+\pi^-\pi^+)}{\mathcal{B}(D_s^+ \rightarrow K^+K^-\pi^+)} = 0.199 \pm 0.004 \pm 0.009 \quad (9)$$

consistent, within 1 standard deviation, with the Particle Data Group [12] value:  $0.265 \pm 0.041 \pm 0.031$ . It is also

TABLE III. Summary of systematic uncertainties on the  $\mathcal{B}(D_s^+ \rightarrow \pi^+\pi^-\pi^+)/\mathcal{B}(D_s^+ \rightarrow K^+K^-\pi^+)$  ratio.

Source	Systematic uncertainties (%)
MC statistics	0.9
$\Delta m$ cut	1.5
Likelihood cut	2.6
Particle identification	3.0
Total	4.3

consistent with a recent measurement from CLEO [18]:  $0.202 \pm 0.011 \pm 0.009$ .

The study of the  $D_s^+ \rightarrow K^+K^-\pi^+$  decay can give new information on the  $K\bar{K}\mathcal{S}$  wave. This information together with the results reported in this analysis will enable new measurements of the  $f_0(980)$  couplings to  $\pi\pi/K\bar{K}$ .

## VIII. CONCLUSIONS

A Dalitz plot analysis of approximately 13 000  $D_s^+ \rightarrow \pi^+\pi^-\pi^+$  has been performed. The fit measures fractions and phases for quasi-two-body decay modes. The amplitude and phase of the  $\pi^+\pi^-\mathcal{S}$  wave is extracted in a model-independent way for the first time. We also measure with high precision the  $\mathcal{B}(D_s^+ \rightarrow \pi^+\pi^-\pi^+)/\mathcal{B}(D_s^+ \rightarrow K^+K^-\pi^+)$  ratio.

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